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STRATEGY FOR D-^{3}He FUSION DEVELOPMENT

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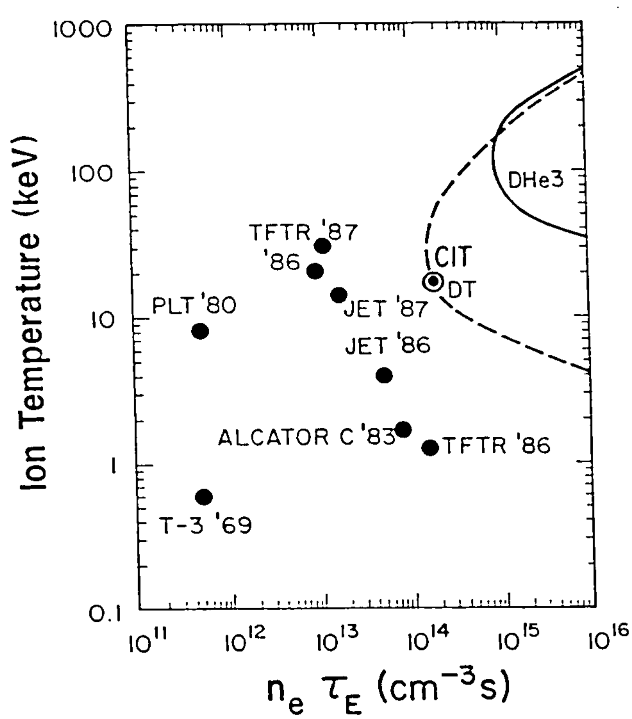
Issues for D-^{3}He Fusion Development

- Physics
- Fueling
- Power Density
- First Wall Heat Flux
- Materials
- Plasma Heating
- Current Drive
- High-Efficiency Operation
- Safety
- Environment
- Licensing

Progress Toward Fusion Ignition Conditions



Plasma Fueling is More Difficult For D-^{3}He Fusion Reactors

- Fuel pellets ablate more quickly in hotter plasmas and pellet fabrication is difficult

- Fueling by plasma injection appears to be a very promising option

  –Marshal gun plasma fueling was done successfully on Tokapole II

  –Compact toroid fueling (proposed for U.S. ITER/TIBER) allows injection velocities of 100's of km/s

- Neutral beam fueling is also an option

Power Density Should be Measured in kWe/kg not in kW_{fus}/V_{plasma}

- Traditional power density arguments based on $\beta^2 B^4$ scaling are only very rough indicators of performance

- Reduced neutron flux helps greatly

  –Reduced shield thickness and mass

  –Reduced magnet size and mass

  –Increased B field at plasma

- Direct conversion increases net electric power

- Many configurations can increase B fields in the fusion core

HARD	MODERATE	EASY
S/C Tokamak	Copper Tokamak	RFP
Stellarator	Heliotron	FRC
Torsatron		Tandem Mirror
		Spheromak
		EBT

Increased Heat Fluxes for D-^{3}He Reactor First Walls are Manageable

- Zeroth order increase in heat flux is a factor of five

- Reduced neutron shielding allows larger first wall radius and area

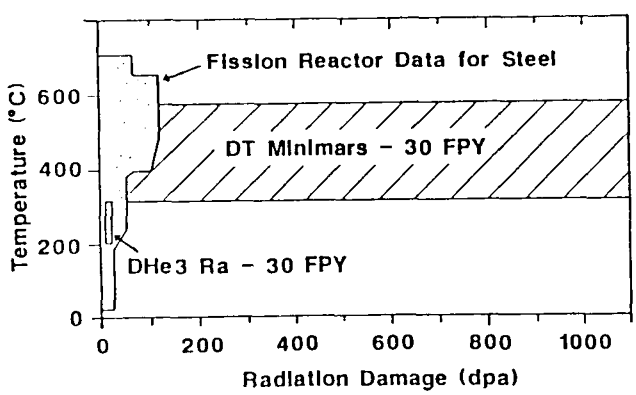
- Present conceptual DT tokamak reactors are designed well below technologically allowable heat flux limits (~4 MW/m^2)

  –Ratio of approximate technological limit to reactor design point:

DESIGN	RATIO
STARFIRE	4.4
NUWMAK	3.6

Materials Suitable for D-^{3}He Reactors Have Already Been Tested

- The fission reactor program has provided ample data on neutron damage to materials in the range of temperatures and fluences required for a D-^{3}He fusion reactor



D-^{3}He Plasma Heating is Similar to D-T Plasma Heating in Difficulty

- Ion Cyclotron Range of Frequencies (ICRF) heating of ^{3}He has been successfully demonstrated on JET
  - –Produced 50 kW of D-^{3}He thermonuclear fusion power
  - –Average ^{3}He energy rose to 200-500 keV (minority heating mode, D background)

- Electron Cyclotron Range of Frequencies (ECRF) heating requires the same technology

- Higher D-^{3}He plasma temperatures will lead to somewhat higher neutral beam energy requirements

- Adiabatic compression should be easier because the plasma will be hotter and more ideal (in an MHD sense)

Current Drive Physics and Technology Must be Better Understood before Judging with Respect to D-^{3}He Fusion

- Higher electron temperatures for D-^{3}He make current drive easier

- D-^{3}He fusion probably requires larger plasma currents

- Current drive by synchrotron radiation is easier for D-^{3}He reactors

Direct Conversion to Electricity Should Be Vigorously Pursued

- Potential net plant efficiencies of 70%
- Electrostatic direct conversion
  - –Periodically focussed
  - –Venetian blind
- Electromagnetic direct conversion
  - –Adiabatic compression/decompression cycles
  - –Synchrotron radiation conversion using rectennas
- Very high temperature thermal cycles
  - –MHD conversion
  - –Radiation boiler
  - –Synfuel production

Utilities Want Ease of Licensing

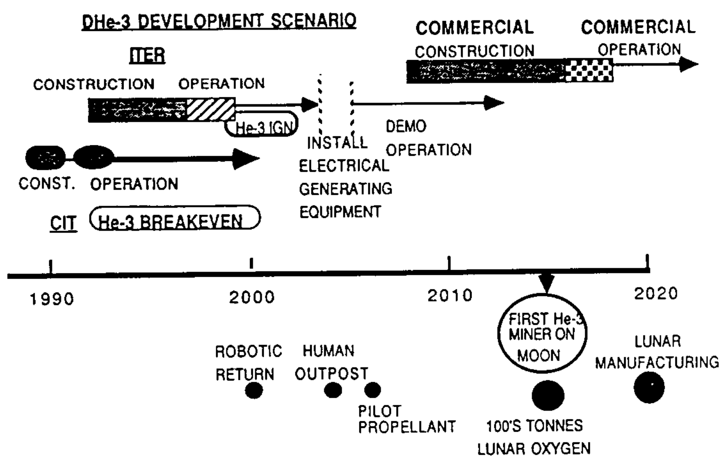
- Utility and Industry fusion advisory committees repeatedly stress that safety, environment, protection of investment, and licensing should be major thrusts of fusion power development
- D-^{3}He fusion will assure:
  - –Safety because of the low radioactive volatile inventory
  - –Environmental quality because only very low-level (Class A) wastes will remain at end of reactor life
  - –Protection of investment due to low afterheat (no meltdown even a month after shutdown under adiabatic conditions)
  - –Ease of licensing because a D-^{3}He fusion reactor will truly be inherently safe

D-^{3}He Fusion Development Requires Harder Physics But Easier Technology

D-^{3}He Physics and Technology Versus D-T

• Physics	Somewhat harder
• Fueling	Harder
• Mass Power Density	Nearly equal
• First Wall Heat Flux	Manageable
• Materials	Much easier
• Plasma Heating	Similar
• Current Drive	Similar
• High-Efficiency Operation	Much easier
• Safety	Much easier
• Environment	Much easier
• Licensing	Very much easier

D-^{3}He Fusion and Lunar ^{3}He Procurement Could Occur on a Consistent Timescale



LUNAR BASE DEVELOPMENT SCENARIO

Strategy for D-^{3}He Fusion Development

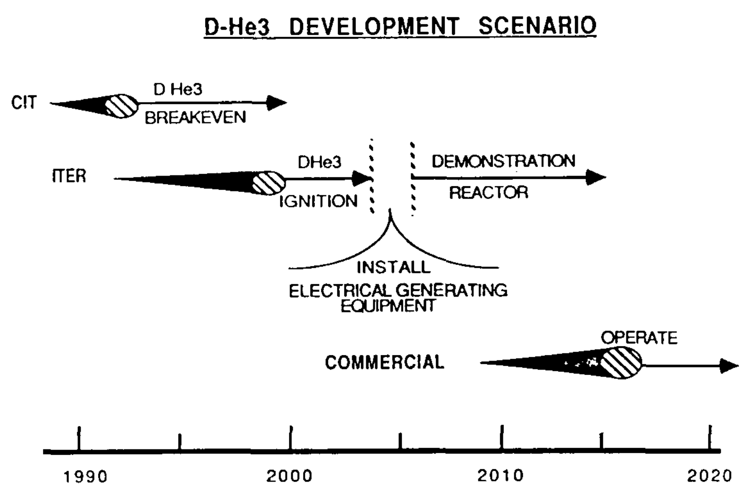
D-^{3}He TOKAMAK DEVELOPMENT PATH

1) CIT (Compact Ignition Tokamak): Design planned D-T device to achieve D-^{3}He $Q \geq 2$ in an early phase of operation

2) ITER (International Tokamak Experimental Reactor): Design planned D-T device to achieve D-^{3}He ignition in an early phase of operation

3) DEMO (Demonstration Reactor): Add power conversion and other systems to ITER in a follow-on stage to demonstrate D-^{3}He commercial reactor viability

D-^{3}He Fusion Development Requires Harder Physics But Easier Technology



HIGH-LEVERAGE D-^{3}He CONCEPTS PATH

1) Investigate whether a D-^{3}He operation phase in presently planned major experiments would provide significant information

2) Investigate the feasibility and cost of a D-^{3}He ignition (high-Q) experiment

3) Quantify advantages and disadvantages of the D-^{3}He reactor embodiment of candidate, high-leverage concepts

Tokamak Plasma Power Balance Computer Code
Prof. G.A. Emmert

Ingredients of the model:

1) Charged Particle Heating - a fraction of the fusion power goes to the ions; based on slowing down theory from the Fokker-Planck equation

2) Fast Ion Pressure

3) Bremsstrahlung - with relativistic corrections

4) Synchrotron Radiation - uses Trubnikov's "universal" formula

5) Energy transport across the magnetic field - uses empirical formulas for τ_E: Kaye-Goldston or ASDEX H-Mode

6) Electron-Ion Energy Transfer - classical + relativistic corrections

7) MHD Limits - uses the Troyon β_c formula

8) Particle Confinement - Ash accumulation

$$\tau_p = \tau_E$$

9) Density and temperature profiles are legislated

$$n \sim (1 - r^2/a^2)^{\alpha_n}$$

$$T \sim (1 - r^2/a^2)^{\alpha_T}$$

It does not include:

1) 2 component mode of operation - $\langle \sigma v \rangle$ is Maxwellian averaged

2) Impurities other than the fusion produced ash

3) Current drive considerations

The code calculates the ignition margin, M,

$$M = \frac{P_{\text{FUSION}}}{\sum P_{\text{LOSSES}}}$$

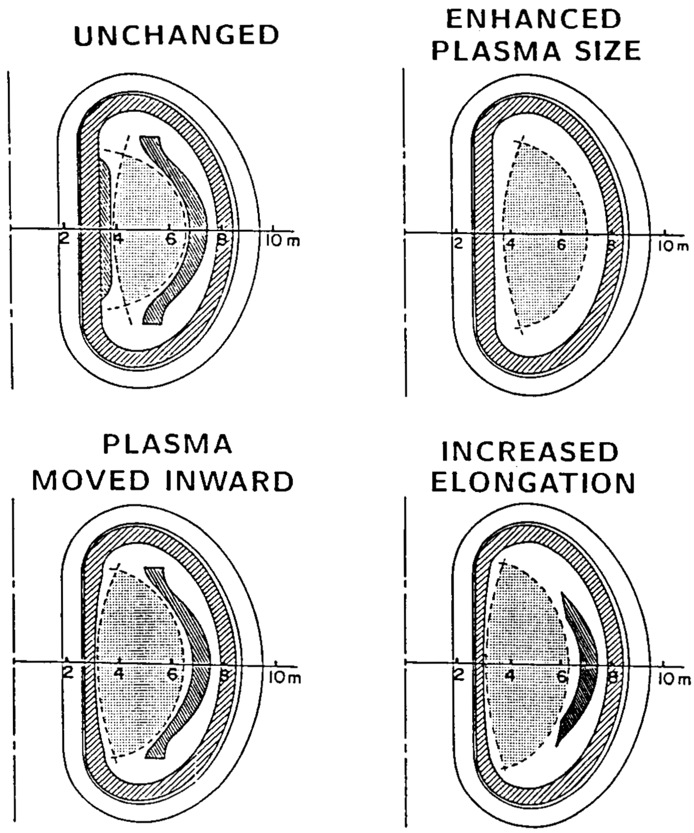
and the energy multiplication,

$$Q = \frac{P_{\text{FUSION}}}{P_{\text{inj}}} = \frac{M}{1 - M}$$

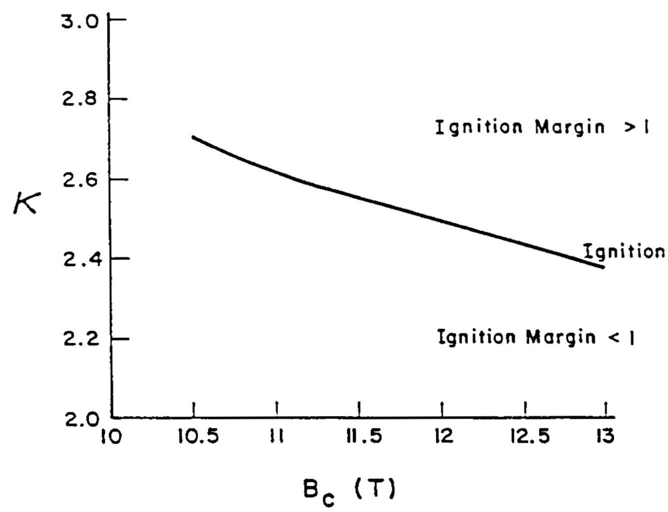
for a given T_i or T_e. The temperature of the other species is determined by a power balance on that species.

If the plasma is ignited, then $M > 1$ and $P_{\text{inj}} < 0$. One has to enhance the energy loss to maintain the plasma at that temperature.

D-^{3}He Operation Allows Inboard Shielding To Be Reduced and a Magnetic Field Increase



Achieving D-^{3}He Ignition Will Require Many Trade-Offs



Power Balance Calculation Summary

- Under present NET (Next European Torus) scaling guidelines, a D-^{3}He plasma would ignite in an early phase of a modified ($\sim$10% cost penalty) D-T ITER experiment

  –Highest-impact modifications would be to reduce shielding thickness, move the plasma to a smaller major radius, and increase the magnetic field at the coils

  –CIT could similarly achieve $Q \geq 2$

- Under the most pessimistic of the scaling laws, neither a D-^{3}He plasma nor a D-T plasma would ignite in ITER unless the size were increased

- The question of whether D-^{3}He physics could be demonstrated on the next generation D-T experiments deserves careful consideration, even at modest cost increase for the device

REQUIRMENTS OF DHe-3 PHYSICS AND TECHNOLOGY VS THE DT CYCLE

AREA	HARDER	SIMILAR	EASIER
PHYSICS	■		
FUELING		■	
PLASMA HTG		■	
CURRENT DR		■	
FW HT FLUX		■	
MASS POWER DENSITY		■	
MATERIALS			■
HIGH EFF. OP			■
SAFETY			■
ENVIRONMENT			■
LICENSING			■

Conclusions

- D-^{3}He fusion faces a more difficult physics development path but an easier technology development path than does D-T fusion

- Early D-^{3}He tests in next generation (CIT and ITER) D-T fusion experiments might provide a valuable D-^{3}He proof-of-principle at modest cost ($\sim$10%)

- At least one high-leverage alternate concept should be vigorously pursued

- Space applications of D-^{3}He fusion are critically important to large-scale space development